Effects of elevated CO_2 and temperature on rice brown planthopper, *Nilaparvata lugens* (Stål) populations in India

Sunil Vailla[1], Sampathkumar Muthusamy[2]*, Chiranjeevi Konijeti[1], Chitra Shanker[1] and Jhansi Lakshmi Vattikuti[1]

[1]ICAR- Indian Institute of Rice Research, Rajendranagar, Hyderabad - 500030, Telangana, India.

[2] ICAR-National Bureau of Agricultural Insect Resources - Bengaluru-560024.

***Corresponding author:**

Dr. M. Sampathkumar, Scientist,
National Bureau of Agricultural Insect Resources,
P. Bag No: 2491, H.A. Farm Post,
Bellary Road, Bengaluru-560 024,
Karnataka, India.
Phone: +91(080) - 2351 1982; 98
+91(080) - 2341 1961
Email: ento_sam@yahoo.co.in

Abstract

Two populations of the brown planthopper (BPH), *Nilaparvata lugens* (Stål) (Homoptera: Delphacidae) were collected from two hotspot locations of India – Ludhiana (Punjab) in the north and West Godavari (Andhra Pradesh) in the south and their biological parameters were studied under ambient conditions. Results showed that the above two populations were notably different in three out of five biological parameters recorded. The response of these two populations to climate variables *viz*., elevated temperature and increased levels of CO_2 was assessed. These conditions

prolonged the nymphal duration (14.2 days) and lowered female longevity (9.6 days), fecundity (155.5 eggs/ ♀) and nymphal feeding rate (14.3 mm^2) as compared to ambient CO_2 and temperature across the populations. Honeydew excretion by adults was significantly higher at elevated CO_2 than at the ambient level. At elevated CO_2 and higher temperature, Ludhiana population recorded significantly longer nymphal duration (15.9 days) and decreased amount of honeydew excretion by nymphs (13.8 mm^2) as compared to the parameters recorded at elevated CO_2 and ambient temperature (12.8 days and 32.8 mm^2, respectively). In contrast, West Godavari population recorded significantly reduced female longevity and fecundity under elevated CO_2 and higher temperature. Elevated CO_2 *per se* did not adversely affect BPH biology across populations but with the concomitant increase in temperature, populations showed varying response. Location specific mitigation strategies for management of hoppers will be required to address the varying responses of populations to climate variables.

Key words: BPH, Fecundity, Honeydew, Ludhiana, West Godavari.

Introduction

Global climate change is no longer for prediction but a reality. The global average temperature which has now increased by 0.6^{o}C is projected to further increase by 1.4 - 7.5^{o}C; whereas the elevated atmospheric CO_2 level at 380 ppm presently is expected to reach 560 ppm by the end of 21st century[1]. It is also predicted that temperature increase of about 2 to 3^{o}C would result in 5 to 10% yield loss in the rice crop, if no proper counter measure was adopted between 2030 and 2050[2]. Climate change is expected to have great impacts on crop pests directly as well as through their host plants indirectly[3]. Many species of herbivorous insects tend to show altered behaviour under CO_2 enrichment and has been studied extensively in many insects[4,5,6,7,8]. The consequences differ among species and include retarded growth rate, increased nymphal development time, higher mortality rates,[9,10] accelerated development of eggs and larvae and delayed emergence of adults[11]. The brown planthopper (BPH), *Nilaparvata lugens* (Stål) (Homoptera: Delphacidae) is one of the most serious pests of rice in both temperate and tropical regions of East and South Asia and has reached outbreak levels over the past few years[12]. It is known for its seasonal migration and '*r*' strategy pattern of life. It directly damages the plant by sucking phloem sap, causing hopper burn, and also by transmitting viral diseases[13]. It has emerged as the major pest of rice in India only after 1971, with cultivation of short statured high yielding and nitrogen-responsive varieties. Widespread outbreaks of brown planthopper causing heavy yield losses were observed in recent years[14,15]. In 2005-2006, more than 485,000 hectares of rice in southern Vietnam were severely affected by viral diseases spread by BPH, resulting in losses valued at US$120 million[16]. The planthopper populations from different countries and areas within countries differ in their responses to rice varieties with the

same resistance genes[17,18]. Similar differences may be reflected in their response to climate change. There is scant information available on the impact of elevated CO_2 and temperature individually and in combination on BPH and the variations in response of populations from different geographical regions. Hence, the present study was envisaged to assess the interactive effects of elevated CO_2 and temperature on BPH populations collected from two different geographical regions of India which are hotspots for the outbreak of this insect.

Materials and methods

CO_2 chambers

A specially designed closed climate controlled chamber was constructed with a total dimension of 10'x8'x10'. It had three chambers each of 2.5'x8'. The chambers were maintained at three levels of CO_2 concentration and temperature combinations, continuously, at the ICAR-Indian Institute of Rice Research, Hyderabad (Latitude-17°10"N, Longitude-78°E, Altitude -542m) as follows.

1. Ambient CO_2@ 380±25ppm and ambient temperature (aCO2+aT),
2. Elevated CO_2@550±25ppm and ambient temperature (eCO2+aT) and
3. Elevated CO_2@550±25ppm and elevated temperature (eCO2+eT).

Fully automatic control and monitoring system with CO_2 sensors, Programmable Logic Controller (PLC) and Supervisory control and data acquisition (SCADA) programme to monitor the desired CO_2 level within the chambers, was established in an anteroom and the climate variables as listed above were maintained throughout the study period. CO_2, temperature and humidity were recorded continuously during the experiment. Temperatures were 31°C/26°C for day/night cycle and relative humidity 70-80% for

ambient temperature and 34°C/29°C for elevated temperature and relative humidity was 60-70%.

Insect material

BPH populations were collected from two different states of the country. One population was collected from Ludhiana of Punjab state, falling under hot semi arid climatic conditions representing north-west India where rice crop is grown only during June to November (Wet season). The second population was collected from West Godavari District of Andhra Pradesh state which falls under hot sub humid to semi arid conditions, where rice is grown in two seasons (Dry and Wet). The populations were individually reared on young rice seedlings of susceptible cultivar TN1, using modified Japanese method[19,20] in flexi cages to avoid mating and intermingling of the two populations in a green house at the Indian Institute of Rice Research, Hyderabad, India.

Biological parameters

Baseline biological data of populations

The biological parameters such as nymphal survival, nymphal duration, longevity and fecundity of the two populations were studied in the laboratory under ambient conditions. Newly emerged first instar nymphs were used for this experiment. A single forty- five days old rice plant (*cv* TN1) was taken in a glass test tube (25x200mm *dia*) containing Hoagland's nutrition media up to 5cm depth and twenty nymphs were released into it. When plants showed yellowing due to feeding it was replaced with plants of the same age. The level of Hoagland solution was maintained by topping regularly. Observations were recorded on various biological parameters.

Nymphal duration

Five pairs of adults from each population were collected from the stock culture and reared in CO_2 chambers designated as (F_0) generation; subsequently the newly hatched nymphs of F_1 generation were transferred singly on 30 days old TN1 plant placed in Hoagland solution inside a glass test tube (25x200mm). Forty replications were maintained in each chamber. The rice seedling was replaced every alternate day. Nymphal duration was calculated from the day of hatching up to adult emergence.

Fecundity and longevity of adults

One pair of newly emerged adults of F_1 generation was released on potted plant of TN1 (45 days old), covered with a mylar cage. Every 3rd day, adults were transferred to fresh 45 days old TN1 plants until the death of adults. Observations were also recorded on nymphal hatching every day until no nymphal hatching was observed for four consecutive days. Survival of the male and female hoppers was recorded and longevity was calculated as the period from emergence to death.

Honeydew excretion test

Feeding behavior of the two populations at three different treatments was estimated by honeydew excretion of third instars nymphs and newly emerged brachypterous females individually as per protocol[21]. Five third instar nymphs or a one day old brachypterous female starved for 2h, were released on 30 days old rice seedlings (*cv* TN1) at the three leaf stage. Each treatment was replicated thrice and the area of honeydew excretion was measured from the scanned image of the filter paper using *Image J* software.

Data analysis

Data collected for each variable were analyzed by a General Linear Model (GLM) SYSTAT 12 (Systat software Inc. Chicago IL) with CO_2 concentration and temperature included as factors. Datasets were transformed where necessary to satisfy assumptions of normality and homogeneity of variances. Where a significant interaction between the two factors occurred in the GLM analysis, a *post hoc* comparison of means was carried out. For datasets with homogenous variances, LSD test was used. Where heteroskedasticity occurred that could not be removed *via* data transformation, the Games and Howell method was used to compare means.

Results

Baseline biological data of populations

The two populations showed significant differences for various biological parameters. Lower nymphal survival (48.5 %) was observed in West Godavari population as compared to ninety per cent in Ludhiana population (Table 1). The latter showed prolonged nymphal duration in brachypterous female and male and macropterous male as compared to West Godavari population. Irrespective of wing morphs, female and male hoppers took longer to develop in the Ludhiana population (Table 1). Similar trend was observed in brachypterous and macropterous forms irrespective of gender. The development of macropterous female forms was very low in the study as food was not a constraint. The longevity of brachypterous female and male was significantly higher in West Godavari population. On the other hand, the fecundity was higher in Ludhiana population (116eggs/♀) as compared to West Godavari population (62.5eggs/♀).

Nymphal development

The nymphal duration did not differ significantly in West Godavari population among the treatments. But in Ludhiana population it was significantly prolonged in eCO_2+eT (15.9 days) when compared to other treatments. Across the treatments, nymphal duration was highest in eCO_2+eT (14.2 days). Across the populations, the population from West Godavari had lesser developmental duration (12.8 days) than that of Ludhiana (13.8 days) (Figure1& Table2).

Longevity of adults

In the West Godavari population, female longevity did not differ significantly among the CO_2 treatments (Figure 2a & Table 2). On the other hand, the female longevity in Ludhiana population was significantly lesser in eCO_2+eT (10.4 days) than aCO_2+aT (15.0 days). Across the treatments, female longevity was significantly reduced at eCO_2+eT (9.6 days) compared to other treatments. Across the populations, female longevity was significantly higher in Ludhiana population (12.3 days) than in West Godavari population (10.3 days). However, male longevity did not differ significantly across the treatments and populations (Figure 2b & Table 2).

Fecundity of female adults

Fecundity increased in West Godavari population, at eCO_2+aT (275.5eggs/♀) compared to eCO_2+eT (134.2eggs/♀) and aCO_2+aT (113.2eggs/♀) whereas it was not significantly different in the Ludhiana population. Across the treatments, the fecundity was significantly higher at eCO_2+aT (251.3eggs/♀) compared to eCO_2+eT

(155.5eggs/♀) and aCO_2+aT (188.3eggs/♀). However, across the populations, the two did not differ significantly (Figure 3 & Table 2).

Feeding assessed by honey dew secretion

Honeydew excretion by third instar nymphs of West Godavari population was on par in all the treatments. Ludhiana population showed significant difference between eCO_2 treatments: lower amount of honeydew was excreted by third instar nymphs at eCO_2+eT (13.8 mm^2) compared to eCO_2+aT (32.8 mm^2). Similarly, across the treatments, significantly lower amount of honeydew was excreted at eCO_2 +eT (14.3 mm^2) compared to eCO_2+aT (29.6 mm^2) and aCO_2+aT (21.8 mm^2) though the difference among the populations was not significant (Figure 4a & Table 2).

Honeydew excreted by the brachypterous females showed significant differences in West Godavari population, the feeding under eCO_2 treatments were on par, but lower amount of honeydew was excreted by the adults under aCO_2+aT (166.3 mm^2) compared to other treatments (Figure 4b). In Ludhiana population, though higher amount of honeydew was excreted by female adults under eCO_2+aT (323.0 mm^2), it was not statistically significant. Across the treatments, honeydew excretion was significantly higher under eCO_2+aT (284.0 mm^2) compared to aCO_2+aT (206.9 mm^2) but temperature fluctuations did not have a significant influence. Across the populations, higher amount of honeydew excretion was noticed in Ludhiana population (274.4 mm^2) than in West Godavari population (213.3 mm^2) (Figure 4b & Table 2).

Discussion

Climate change is associated with warming, elevated CO_2 and regionally changed precipitation[22]. Temperature directly influences the survival, development and abundance of insects profoundly. Insects inhabiting the colder climates with marked seasons have better tolerance to thermal extremes. Global warming may benefit such insects which are currently exposed to cooler temperatures that are lesser than their optima[23]. Insects inhabiting the tropical regions are already living at environmental temperatures close to their optimum and any further increase may have adverse effects.

Environmental heterogeneity affects the phenotypic expressions of insects[23]. Similarly, biological evidence suggests that rice planthoppers show significant geographic structure[19]. Our studies too indicate geographical variations exist in planthoppers with respect to biological parameters *viz*., survival, developmental period, longevity, fecundity and wing morphs.

When geographical variations exist in populations without climate stress, the response to climatic variables may also differ. In our results, elevated temperature with increased levels of CO_2, significantly affected the biological parameters of BPH. It prolonged the nymphal duration and lowered longevity, fecundity and nymphal feeding rate. When the temperatures were lower than the optimum range or above optimum range, it was observed that biological functions like feeding, rate of development and longevity were lowered while nymphal duration was prolonged in BPH[24]. Our results are in line with earlier findings[25] that the duration of nymphal growth was shorter at a mean temperature of 30^{o}C, and prolonged with increased temperature. Other studies have reported that temperature between 25^{o} and 30^{o}C was optimal for egg and nymphal

development of BPH[26,27,28,29,30] whereas temperatures above 30°C, was found to be unfavourable for insect survival[27,28,30,31].

Female longevity was significantly reduced under elevated CO_2 and elevated temperature in Ludhiana population. A similar trend was observed in West Godavari population though not statistically significant. However, male longevity did not show any significant difference in both populations. The yellow sugarcane aphid, *Sipha flava* showed shorter longevity at elevated CO_2 (500 ppm) and elevated temperature (28°C) than at the same CO_2 conditions but lower fluctuating temperatures[32]. The female longevity of *S. flava* was also found to be shorter at elevated CO_2 (700 ppm) and elevated temperature (28°C) than ambient CO_2 and temperature [32].

We observed that the fecundity of BPH increased at elevated CO_2 levels but, elevated temperature decreased the fecundity of BPH across the treatments. The number of eggs laid by BPH was found to be lower, at higher temperature regimes of 34.0 and 36.0°C and observed that these increased temperatures were not suitable for egg laying and development of BPH[33]. The number of eggs laid by BPH decreased rapidly as the temperature increased[34]. However, in contrast it was reported that fecundity was higher at elevated temperature with elevated CO_2 than at ambient temperature with ambient CO_2[35]. This study was however conducted in a temperate region which has been hypothesized to benefit insects that are exposed to cooler temperatures[36]. The elevated temperature in our case, being in a tropical region, was a +3°C increase from 31/26 to 34/29°C (day/night cycle) which might have lead to decreased egg laying capacity of BPH. Further, it was observed that fecundity of BPH showed varying results between populations with respect to elevated temperature and CO_2. Population from West Godavari which is a coastal region showed decreased rate of fecundity at elevated

253 temperature and elevated CO_2 whereas the Ludhiana population exposed to distinct hot
254 and cooler climes, was not influenced by elevated temperature and elevated CO_2. The
255 optimum temperature for survival and reproduction varies between insect species and
256 populations of each species[22]. Our results indicate that the feeding rate of third instar
257 nymphs was more influenced by the combined effect of elevated CO_2 and temperature
258 in both the populations, which was in accordance with earlier reports[5,8] that elevated
259 temperature may directly reduce feeding in insects or the reduced water content in
260 stem parts and altered osmotic potential in the phloem-sap may reduce the feeding rate.
261 In case of adults, elevated CO_2 increased feeding in both the populations, while
262 temperature did not have a significant impact. On the other hand, earlier literature states
263 that high temperature exposure reduced feeding activity and honeydew production in
264 both life stages (nymphs and adults) of *N. lugens*[37]. This clearly indicates that insects
265 from tropical and temperate regions exposed to different temperature regimes will show
266 varied responses to climate change factors.

267 The average temperature range prevailing at Ludhiana is wider with a minimum
268 temperature being 9.5^{o}C and maximum of 35.3^{o}C while the temperature range at West
269 Godavari is narrower with minimum temperature of 25.3^{o}C and a maximum of 31.8^{o}C
270 (mean of two years 2013-2014). Across all the parameters, Ludhiana population
271 responded positively to climate change with prolonged nymphal duration, higher
272 longevity of females and higher feeding rate. The results of the study indicated that
273 population exposed to a greater temperature range *i.e*. lower/higher temperatures may
274 be positively impacted.

275 The present study revealed that elevated CO_2 (550 ppm) with elevated
276 temperature (+3^{o}C) significantly increased nymphal duration but reduced female

277 longevity, fecundity and amount of honeydew excreted by nymphs of brown
278 planthopper in comparison with those noted at elevated CO_2 and ambient temperature
279 across the two populations studied. However, at elevated CO_2 and ambient temperature,
280 significantly higher amounts of honeydew excretion by adults as compared with those at
281 ambient CO_2 and ambient temperature were recorded. Performance of BPH populations
282 from Ludhiana and west Godavari was notably different in three out of five parameters
283 recorded indicating that populations have a differential response to environmental
284 changes. Future studies should focus more on studying responses of biotypes and
285 populations to projected changes in the environment and formulate risk management
286 strategies specific to each region.

287

288 **Acknowledgments**

289 The research work has been carried out under National Innovations on Climate Resilient
290 Agriculture project funded by ICAR-CRIDA and thankful to our Director, ICAR-Indian
291 Institute of Rice Research for providing facilities and to Dr SR Voleti, the then PI of
292 NICRA for his constant support and encouragement.

293

294

295 **References**

296 1. IPCC., Observed changes in climate and their effects. *Climate Change 2007:*
297 *Synthesis Report* (eds. Pachauri, P.K. and Reisinger, A.). Cambridge University
298 Press, UK, 2007, pp. 8–15.
299 2. Bao-ju, W., Hong-xing, X.U., Xu-song, Z., Qiang, F.U. and Zhong-xian, L.U.,
300 High temperature modifies resistance performances of rice varieties to brown
301 planthopper, *Nilaparvata lugens* (Stål). *Rice Sci.*, 2010, 17, 334−338.
302 3. Coakley, S.M., Scherm, H. and Chakraborty, S., Climate change and plant
303 disease management. *Annu. Rev. Phyto*., 1999, 37, 399–426.
304 4. Bezemer, T.M. and Jones, T.H., Plant-insect herbivore interactions in elevated
305 atmospheric CO_2: quantitative analyses and guild effects. *Oikos.*, 1998, 82, 212–
306 222.
307 5. Mattson, W. and Haack, R., Role of drought in outbreaks of plant-eating insects.
308 *Bioscience*, 1987, 37, 110–118.
309 6. Cheng, W., Sakai, H., Yagi, K. and Hasegawa, T., Interactions of elevated CO_2
310 and night temperature on rice growth and yield. *Agricultural and Forest*
311 *Meteorology*, 2009, 149, 51–58.
312 7. Pritchard, S.G., Rogers, H.H., Prior, S.A. and Peterson, C.M., Elevated CO_2 and
313 plant structure. *A review. Global. Change. Biol*., 1999, 5, 807–837.
314 8. Douglas, A.E., Phloem-sap feeding by animals: problems and solutions. *J. Exp.*
315 *Bot*., 2006, 57, 747–754.
316 9. Coviella, C.E. and Trumble, J.T., Effects of elevated atmospheric carbon dioxide
317 on insect-plant interactions. *Cons. Biol*., 1999, 13, 700–712.

10. Smith, P.H.D. and Jones, T.H., Effects of elevated CO_2 on Chrysanthemum leaf miner, *Chromatomyia syngenesiae*: a green house study. *Global. Change. Biol.*, 1998, 4, 287–291.
11. Buse, A. and Good, J.E.G., Synchronization of larval emergence in winter moth (*Operophtera brumata* L.) and budburst in pendunculate oak (*Quercus robur* L.) under simulated climate change. *Ecol. Entomol*., 1996, 21, 335–343.
12. Hu, G., Cheng, X.N., Qi, G.J., Wang, F.Y. and Lu, F., Rice planting systems, global warming and outbreaks of *Nilaparvata lugens* (Stål). *Bull. Entom. Res.*, 2011, 101, 187–199.
13. Rivera, C.T., Ou, S.H. and Lida, T.T., Grassy stunt disease of rice and its transmission by *Nilaparvata lugens* (Stal). *Plant. Dis. Rep*., 1966, 50, 453–456.
14. Srivastava, C., Chander, S., Sinha, S.R. and Palta, R.K., Toxicity of various insecticides against Delhi and Palla population of brown planthopper (*Nilaparvata lugens*). *Indian. J. Agric. Sci*., 2009, 79, 1003–1006.
15. Sampathkumar, M., Chitra Shanker, Gururaj Katti. and Ravindra Babu, V., Pest survey reports of Entomology, AICRIP, Indian Institute of Rice Research, Hyderabad., 2014, p. 12.
16. Du, P.V., Cabunagan, R.C., Cabauatan, P.Q., Choi, H.S and Choi, I.R., Yellowing syndrome of rice: Etiology, current status and future challenges. *Omon Rice.*, 2007, 15, 94–101.
17. Jairin, J., Phengrat, K., Teangdeerith, S., Vanavichit, A. and Toojinda, T., Mapping of a broad-spectrum brown planthopper resistance gene, Bph3, on rice chromosome 6. *Mol. Breed*., 2007, 19, 35–44.

18. Verma, S.K., Pathak, P.K., Singh, B.N. and Lal, M.N., Indian biotypes of the brown planthopper. *International Rice Research News letter*, 1979, 4, 6.
19. Heong, K.L., Tan, K.H., Garcia, C.P.F., Fabellar, L.T. and Lu, Z., Research methods in toxicology and insecticide resistance monitoring of rice planthoppers. Los Baños, Philippines, International Rice Research Institute, 2011, p. 101.
20. Sunil, V., Jhansi Lakshmi, V., Chiranjeevi, K., Sampathkumar, M., Katti, G.R. and Bentur, J.S., Field collection and rearing of rice brown planthopper (BPH), *Nilaparvata lugens* (Stål) populations in isolated conditions- A Novel Methodology. *Multilogic in Science*, 2018, 8, 207-211.
21. Paguia, P., Pathak, M.D. and Heinrichs, E.A., Honeydew excretion measurement techniques for determining differential feeding activity of biotype of *Nilaparvata lugens* on rice varieties. *Ecolog. Entomol*., 1980, 73, 35–40.
22. Lars Neumeister, *Climate Change and Crop Protection*. Publisher by PAN Asia and Pacific, 2010.
23. Yi Bai, Jia-Jia Dong, De-LongGuan, Juan-YingXie and Sheng-Quan Xu, Geographic variation in wing size and shape of the grasshopper *Trilophidia annulata* (Orthoptera:Oedipodidae): morphological trait variations follow an eco-geographical rule. *Scientific Reports*, 2016, 6:32680.
24. Krishnaiah, N.V., A global perceptive of rice brown planthopper management I - crop climate requirements. *Int. J. Mol. Zool*., 2014, 4, 9–18.
25. Sucheta, R. and Mayabini, J., Effect of high temperature on the multiplication of brown planthopper, *Nilaparvata lugens* (Stal.). *Oryza*, 2012, 49, 288–291.

26. Kulshreshtha, J.P., Anjaneyulu, A. and Padmanabhan, S.Y., The disastrous brown planthopper attack in Kerela. *Indian Farming*, 1974, 24, 5–7.
27. Bae, S.H. and Pathak, M.D., Life history of *Nilaparvata lugens* (Homoptera: Delphacidae) and susceptibility of rice varieties to its attacks. *Ann. Entomol. Soc. Am*., 1970, 63, 149–155.
28. Chiu, M.D., Ecological studies on rice brown planthopper in Chinese. *Taiwan Agric. Q*., 1970, 6, 143–152.
29. Ho, H.S. and Liu, T.H., Ecological investigation on brown planthopper in Taichung district [in Chinese, English summary]. *Plant Prot. Bull (Taiwan).*, 1969, 11, 33–42.
30. Pathak, M.D., Ecology of common insect pests of rice. *Annu. Rev. Entomol*., 1968, 13, 257– 294.
31. Kalode, M.B., Brown planthopper in rice and its control. *Indian farming*., 1976, 27, 3–5.
32. Auad, A.M., Fonseca, M.G., Resende, T.T. and Maddalena, I.S.C.P., Effect of climate change on longevity and reproduction of *Sipha flava* (Hemiptera: Aphididae). *Fla. Entomol.*, 2012, 95, 433–444.
33. Manikandan, N., Kennedy, J.S. and Geethalakshmi, V., Effects of temperature on life history parameters of brown planthopper, *Nilaparvata lugens* (stal). *Afr. J. Agric. Res*., 2015, 10, 3678–3685.
34. Xiaoping, Y., Wu, G. and Cui, H., Effect of high temperatures on the survival and fecundity of brown planthopper (BPH) *Nilaparvata lugens* (Stal). *International Rice Research News letter*, 1992, 17, 26.

387 35. Bao-kun, S., Jian-li, H., Hu Chao-xing, H. and Mao-lin, H., Interactive effects of
388 elevated CO_2 and temperature on rice planthopper, *Nilaparvata lugens*. *J Integr*
389 *Agric.*, 2014, 13, 1520–1529.
390 36. Deutsch, C.A., Tewksbury J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K.,
391 Haak, D.C. and Martin, P.R., Impacts of climate warming on terrestrial
392 ectotherms across latitude. *Proc. Natl. Acad. Sci.*, 2008, 105, 6668–6672.
393 37. Piyaphongkul, J., Effects of thermal stress on brown planthopper, *Nilaparvata*
394 *lugens* (Stal), Doctor of Philosophy, School of Biosciences, University of
395 Birmingham, 2013.
396

397

398 **Table 1. Biological parameters of two populations of brown planthopper, *N. lugens***

Parameters	**West Godavari (Mean±S.E)**	**Ludhiana (Mean±S.E)**	**t value (df)**	**P-value**
Nymphal Survival (%)	48.5±1.5	90.0±0.5	5.36 (18)	0.000
Nymphal Developmental Duration (days)				
Brachypterous (male+female)	13.6±0.2	19.9±0.5	8.42 (104)	0.000
Macropterous (male+female)	12.9±0.2	18.2±1.0	5.26 (25)	0.000
Female (Brachypterous+macropterous)	13.5±0.3	20.8±1.3	7.39 (64)	0.000
Male (Brachypterous+macropterous)	13.3±0.3	18.1±1.2	6.77 (66)	0.000
Brachypterous female	13.6±0.3	21.0±1.3	7.00 (60)	0.000
Brachypterous Male	13.5±0.3	17.8±1.2	4.59 (42)	0.000
Macropterous Male	12.9±0.2	18.6±1.1	5.32 (22)	0.000
Adult Longevity (days)				
Brachypterous Female	15.8±0.7	12.5±0.9	-2.35 (13)	0.030
Brachypterous Male	10.0±1.0	6.1±0.6	-2.90 (8)	0.020
Macropterous Male	6.6±0.8	7.5±0.6	0.83 (9)	0.428
Fecundity (No. of eggs laid/female)				
Brachypterous Female	62.5±7.5	116.4±9.2	-4.40 (11)	0.001

399

400

401 **Table 2. Summary of GLM analysis (ANOVA) results for effect of elevated CO_2**

402 **and temperature on brown planthopper, *N. lugens***

Measurements	Treatments	F-value (*d.f.*)	P-value
Nymphal duration	West Godavari population- CO_2 and temperature	5.43(2)	0.01
	Ludhiana population- CO_2 and temperature	35.01(2)	0.00
	CO_2 and temperature (Across treatments)	13.85(2)	0.00
	Population (Across populations)	5.46(1)	0.00
Longevity female	West Godavari population- CO_2 and temperature	2.98(2)	0.06
	Ludhiana population- CO_2 and temperature	3.30(2)	0.04
	CO_2 and temperature (Across treatments)	4.11(2)	0.02
	Population (Across populations)	4.89(1)	0.03
Longevity male	West Godavari population- CO_2 and temperature	2.16(2)	0.13
	Ludhiana population- CO_2 and temperature	0.88(2)	0.42
	CO_2 and temperature (Across treatments)	0.07(2)	0.93
	Population (Across populations)	3.67(1)	0.06
Fecundity	West Godavari population- CO_2 and temperature	16.71(2)	0.00
	Ludhiana population- CO_2 and temperature	2.53(2)	0.10
	CO_2 and temperature (Across treatments)	3.23(2)	0.03
	Population (Across populations)	0.71(1)	0.40
Honeydew excretion by third instar	West Godavari population- CO_2 and temperature	2.17(2)	0.15
	Ludhiana population- CO_2 and temperature	4.07(2)	0.04
	CO_2 and temperature (Across treatments)	6.58(2)	0.01
	Population (Across populations)	0.09(1)	0.76
Honeydew excretion by female adults	West Godavari population- CO_2 and temperature	9.82(2)	0.01
	Ludhiana population- CO_2 and temperature	3.59(2)	0.09
	CO_2 and temperature (Across treatments)	3.40(2)	0.05
	Population (Across populations)	7.98(1)	0.01

403

404

405 **Figure 1.** n=40 replications for each treatment; aCO_2+aT- ambient CO_2 and ambient
406 temperature; eCO_2+aT- elevated CO_2 and ambient temperature; eCO_2+eT- elevated CO_2
407 and elevated temperature. Different letters on the bars in a panel denotes significant
408 difference (LSD test, p=0.05).
409 **Figure 2a.** n=10-12 for each treatment.
410 **Figure 2b.** n=10-12 for each treatment
411 **Figure 3.** n= 5-10 for each treatment
412 **Figure 4a.** n= 5 for each treatment
413 **Figure 4b.** n= 5 for each treatment.
414
415
416
417
418
419
420
421
422
423
424
425
426
427

Figure 1. Nymphal duration: Effects of CO_2 concentration and temperature on nymphal duration of the brown planthopper, *N. lugens* on TN1 variety.

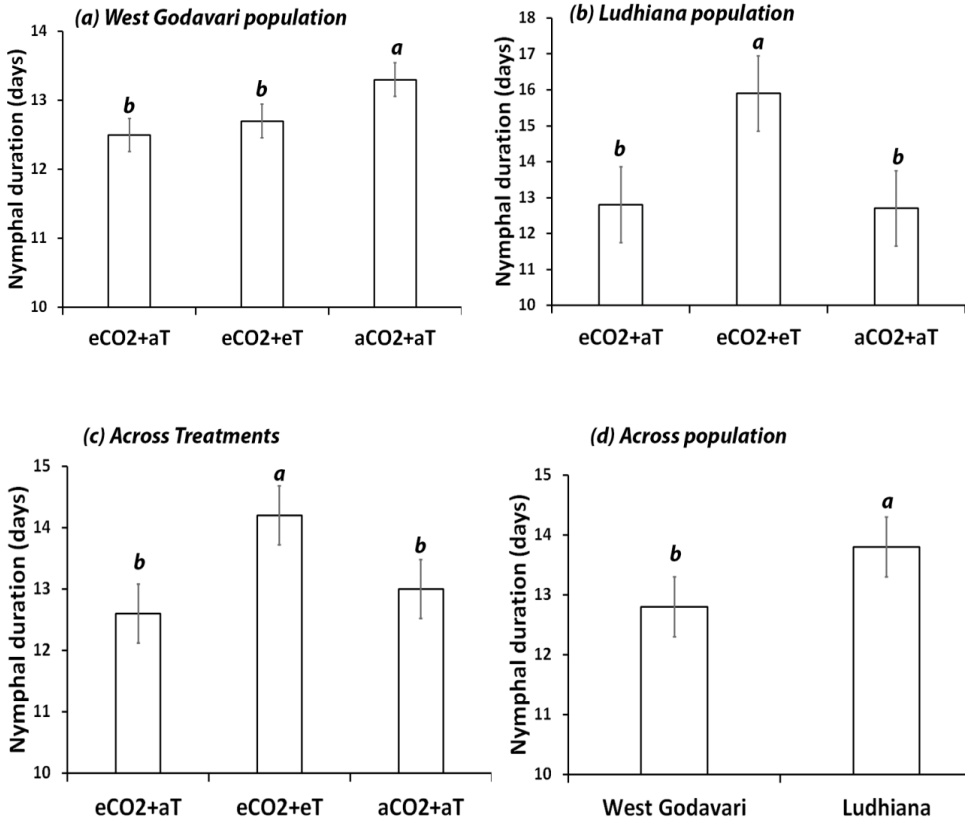

Figure 2a. Female Longevity: Effects of CO_2 concentration and temperature on female longevity of the brown planthopper, *N. lugens* on TN1 variety.

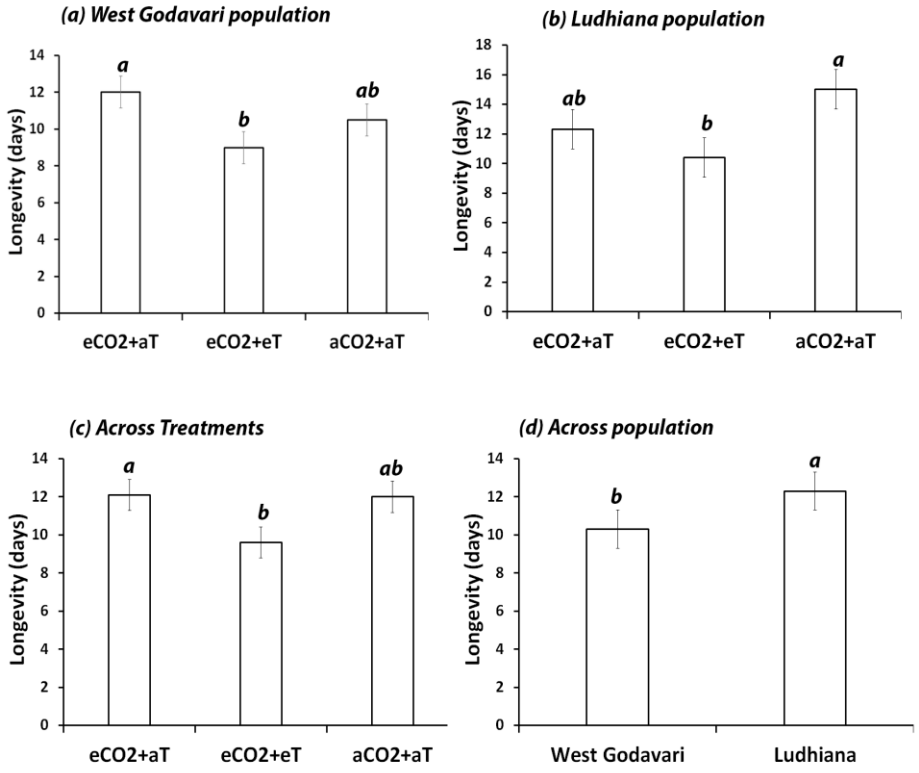

Figure 2b. Male Longevity: Effects of CO_2 concentration and temperature on male longevity of the brown planthopper, *N. lugens* on TN1 variety.

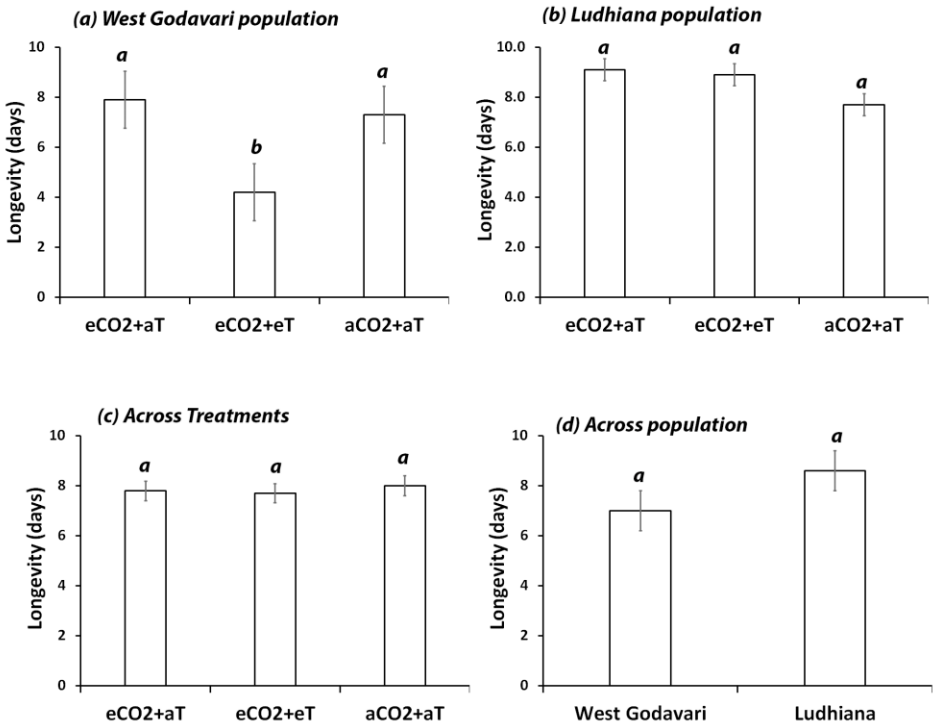

Figure 3. Fecundity of female adults: Effects of CO_2 concentration and temperature on fecundity of the brown planthopper, *N. lugens* on TN1 variety.

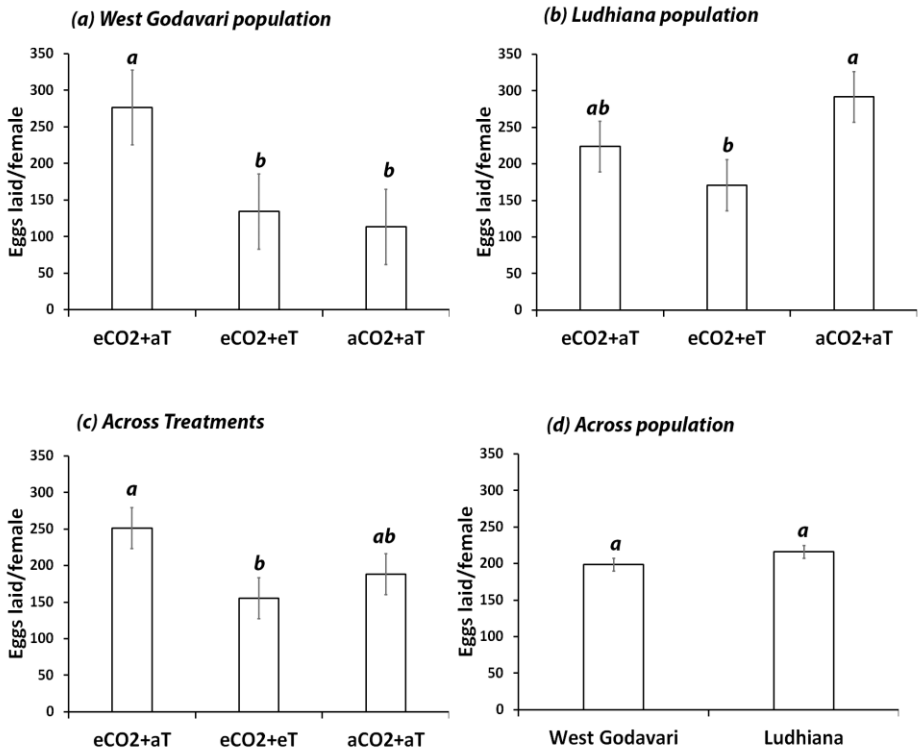

Figure 4a. Honeydew excretion by third instar nymphs: Effects of CO_2 concentration and temperature on honeydew excretion in 24hrs per five third instar nymphs of the brown planthopper, *N. lugens* on TN1 variety.

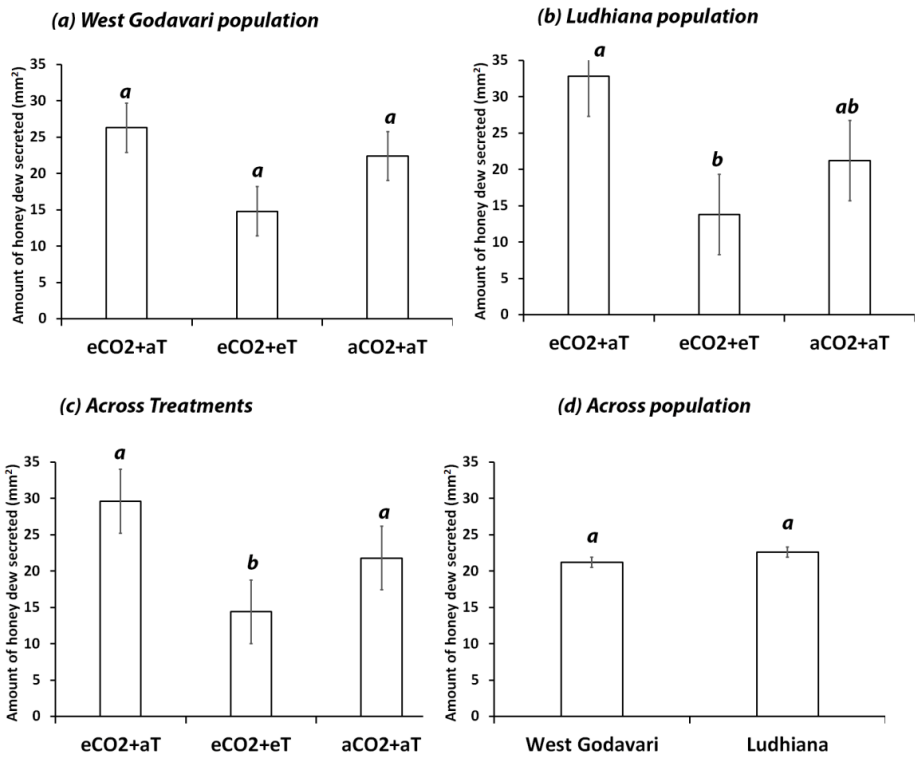

Figure 4b. Honeydew excretion by brachypterous female adults: Effects of CO_2 concentration and temperature on honeydew excretion in 24hrs per five brachypterous females of the brown planthopper, *N. lugens* on TN1 variety.